Use of remote sensing to monitor environmental change of coral reefs;

a case study of the Waiahole Stream region of Kane`ohe Bay

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FINAL REPORT

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ABSTRACT

Kane`ohe Bay, O`ahu, encompasses a special coral reef ecosystem protected by Mokapu Peninsula and an outerlying barrier reef. Multispectral images of the bay have been collected for the School of Ocean and Earth Science and Technology, University of Hawai`i, for various scientific projects. Using part of this data, a small part of Kane`ohe Bay, including the Waiahole Stream mouth, was evaluated and mapped, in order to portray how environmental changes can be monitored using remote sensing multispectral imagery. The objectives of this research are to evaluate the use of remote sensing and multispectral imaging applications to analyze and assess the present condition of coral within the designated study area. A background of human impacts on Kane`ohe Bay is provided in order to understand why monitoring environmental changes is important for this region. The results show the distributions of live coral, algae, and sand on one patch reef within the study area. To assess the health of a coral reef would take more analysis than time permitted, however the results show that remote sensing is a very useful tool for recording and monitoring marine environments. This project can be used as a baseline documentation of the coral reefs in the northwestern sector of Kane`ohe Bay, and may be used for future comparison studies in order to assess the health of the coral in the area.

I. INTRODUCTION

Multispectral imagery is a form of remote sensing, which is a powerful tool combining high tech computer facilities with well established imaging techniques

(Warner *et al.*, 1996). Multispectral mapping of the coral reefs in Kane`ohe Bay can be used as a way to monitor changes in ecosystems, such as coral recovery from sewage deposition and sedimentation. In addition, it may be used as a model for mapping other reef systems in the state, as well as globally. Achieving this level of map data collection is a difficult task in isolated coastal sea and coral reef areas (Kuchler *et al.*, 1988). Remote sensing can meet this challenge. In recent years remote sensing techniques have become increasingly sophisticated, reliable and useful tools for marine research (Kuchler *et al.*, 1988).

Remote sensing images are obtained using electronic cameras that record different wavelengths. Multispectral imagery records two or more wavelength ranges of electromagnetic radiation reflected or emitted from the Earth's surface and then sub-divides the spectrum to produce an image of the environment. Each material within an image reflects a percentage of light, shown in a spectrum of wavelengths (Mouginis-Mark, 1996). The relative contrast in wavelengths reflected enables a person to discriminate among or identify materials. Digital imagery also adds the ability to attribute size, shape and position of the materials. Moreover, these images can be processed rapidly and accurately for GIS and mapping needs, and related products.

Recent works involving remote sensing of coral reefs have been done around the world for many scientific investigations. A case study in French Polynesia conducted by Maritorena (1996), showed that remote sensing can be used to determine the water attenuation near coral reefs. R. Miller and J. Cruise (1995) used remote sensing to show effects of suspended sediments on coral growth. Other research projects by R. Laydoo and J.K. Griffith (1995) have determined coral reef distribution in south west Tobago using remote sensing technology. For further remote sensing application to coral reefs, Kuchler *et al.* (1988) provided an overall review of this high-technology use in marine environments.

A 2-meter per pixel multispectral data set covering all of Kane`ohe Bay was obtained by TerraSystems, Inc., a Hawai`i based company specializing in the field of remote sensing, for the School of Ocean and Earth Science and Technology (SOEST) at the University of Hawai`i. This data set, consisting of 263 images, is currently being used for a project directed by Marlin Atkinson (Dept. of Oceanography faculty) and Eric Hochberg (graduate student, SOEST). The images will be combined to produce a mosaic (one continual pictorial representation) of the coral reefs in Kane`ohe Bay. This mosaic will then be used for various scientific analyses, such as the coral reef distribution and their effect on water currents throughout the bay. A project is under consideration which would use a low earth orbit satellite for monitoring coral reefs world wide and the multispectral mapping of Kane`ohe Bay may be used as a model for designing this satellite.

The objectives of this research are to evaluate the use of remote sensing and multispectral imaging applications for assessing the present condition of coral reefs, specifically in the Waiahole region of Kane`ohe Bay, O`ahu (Fig. 1). Many anthropogenic impacts have adversely affected the coral in Kane`ohe Bay. Part of the purpose of this research was to review the background of Kane`ohe Bay and environs, to evaluate some causes and effects of human activities in the region, with special attention

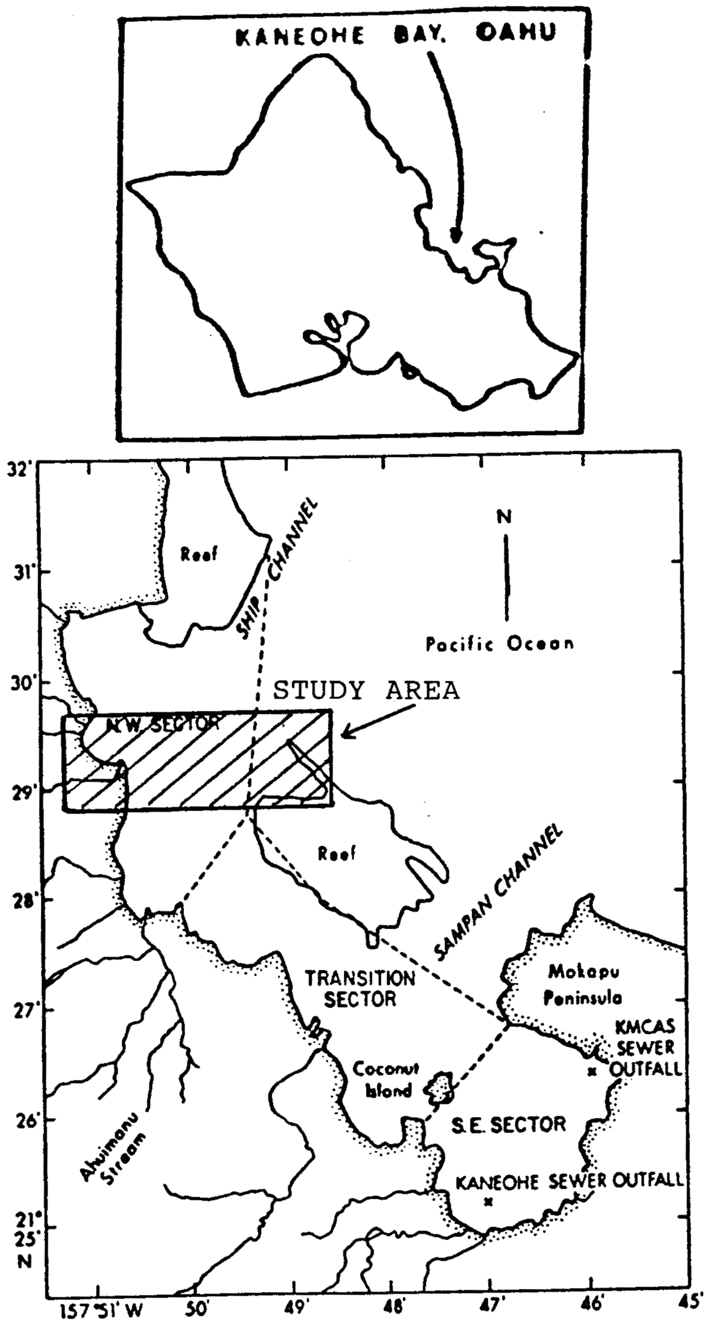


Fig. 1 Kane`ohe Bay, located on the Windward side of O`ahu (Laws, 1993); and selected study area of the Waiahole Stream region within the N.W. Sector of the bay.

to the Waiahole Stream area. Following my selection of this study area, the multispectral imagery data collected by TerraSystems, Inc. for that region, was processed by computer programs. The current condition of coral reefs within the study area was evaluated with concentration on one small patch reef, designated the 'evaluation site'. A map was produced showing the distribution of four components of the evaluation site: live coral, sand, algae, and deep water.

II. METHODS AND PROCEDURES

To meet the objectives of this study, the following tasks were performed.

1. Review literature on remote sensing.

A library search provided many references related to research on remote sensing of marine environments, in addition to general remote sensing technology information.

An Internet search on the subject of remote sensing proved to be very beneficial. SOEST maintains a web page on the Internet which includes a program called *Virtually Hawai`i* in combined efforts with Proxemy Research, Inc. (specializing in remote sensing programs and services) and TerraSystems, Inc., Hawaii. As described on their home page (http://satftp.soest.hawaii.edu/space/hawaii/), the first facet of *Virtually Hawaii* is to build a data base of remote sensing images covering the entire state of Hawaii over a broad range of spatial resolutions. The second facet of *Virtually Hawaii* is to develop several *'Virtual Field Trips'* to places of particular interest in Hawaii in an effort to increase the public's awareness and ability to access, interpret and use remote sensing data.

2. Literature review of Kane`ohe Bay, coral reefs, and Waiahole Stream region.

An initial literature search provided many references beneficial for the understanding of remote sensing of coral reefs, information about Kane`ohe Bay, and the ecology of its coral reefs. Much prior research has been conducted in the bay area concerning terrestrial and marine ecosystems, including impacts and changes in the environment. Waiahole Stream has been of much concern lately with attempts to legally return the stream flow to its natural course.

3. Data Collection.

TerraSystems, Inc. collected 263 multispectral images of Kane`ohe Bay on October 5, 1996. Jonathan Gradie, and pilot of the *Thunder Chicken,* pursued a flight plan at an altitude of 10,000 feet consisting of 14 flight lines fully covering the bay area (Fig. 2). One digital image was collected every 7 seconds at 2-meters per pixel. A multiband camera was used equipped with different filters of 488 nm, 550 nm, 570 nm, and 700 nm. The four filters were determined by Eric Hochberg to differentiate between the wavelengths of different components of the images: live coral, sand, algae, and deep water. TerraSystems, Inc.'s airborne multispectral imaging system has a high spatial resolution which provides an in-depth view at the *local* scale, in contrast to satellite systems which are good for large *regional* scales.

4. Selection of Study Area.

The study area (about 4km x 2km) is located in the northwestern sector of Kane`ohe Bay and includes the mouth of Waiahole Stream (Fig. 3). It incorporates 6 mosaiced digital images of TerraSystems, Inc.'s survey data. It was chosen for its variety

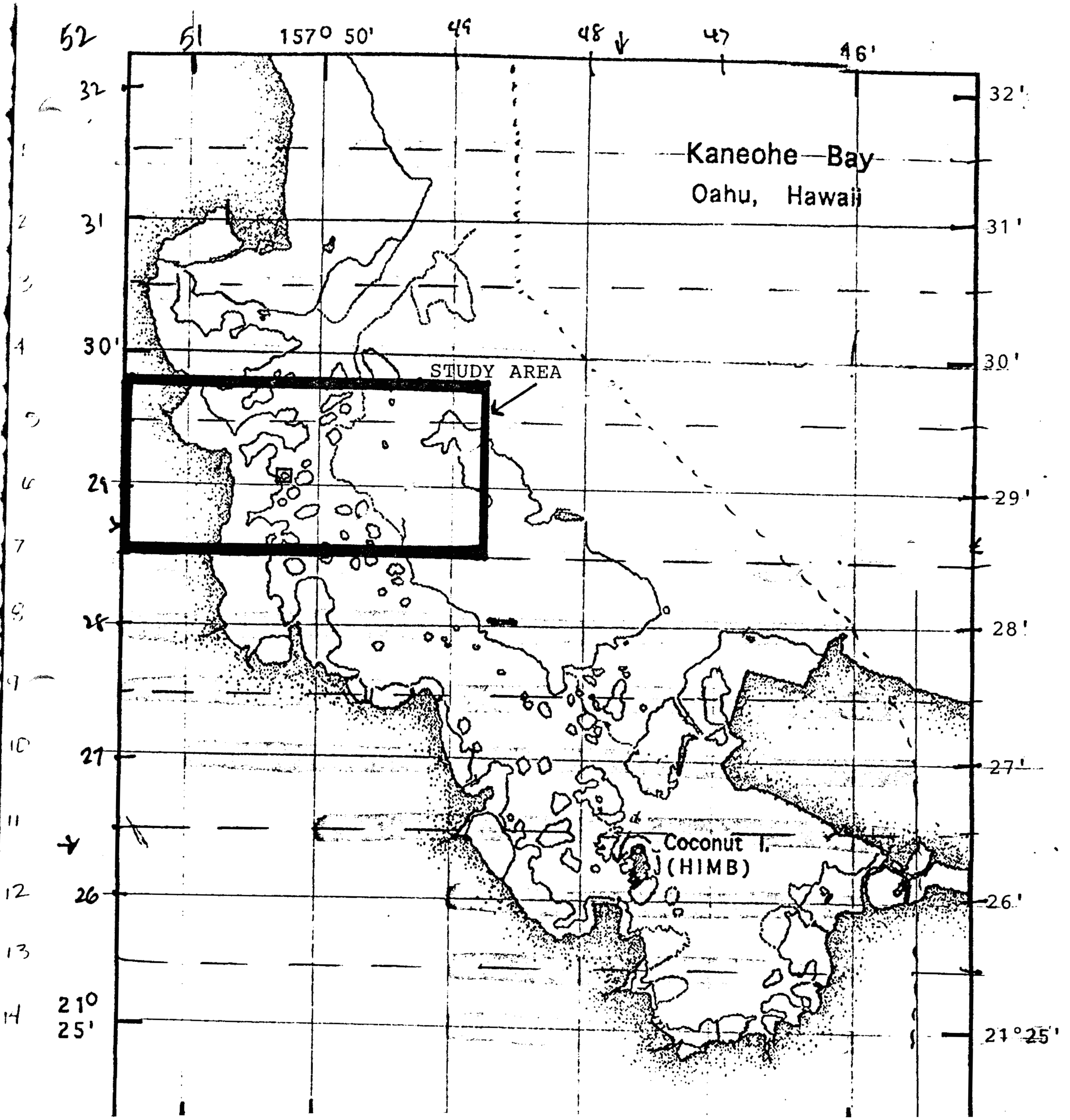


Figure 2. Flightlines used by TerraSystems, Inc. to collect the data consisting of 263 multispectral images. October 5, 1996; Kane'ohe Bay, O'ahu. Source: TerraSystems, Inc.

Waiahole Stream Study Area

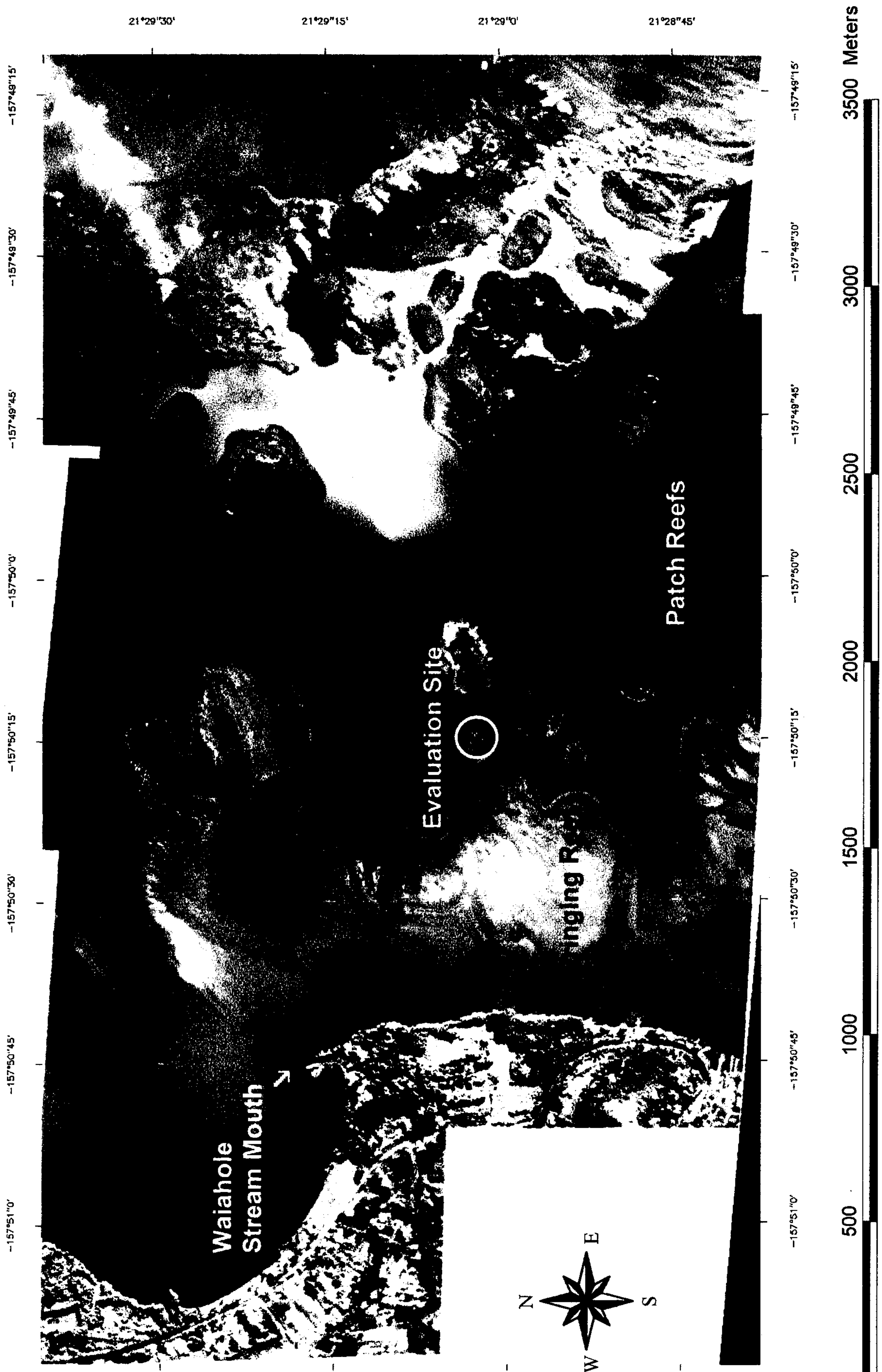


Fig. 3
Selected Study Area.

of components: land, stream, delta, fringing reef, patch reefs, lagoon, and barrier reef. One small patch reef was designated to be used as the evaluation site to represent the total project area (Fig. 4). This site was analyzed by Eric Hochberg using his preliminary algorithms developed for a computer program to label four specific materials in remotely sensed images: live coral, sand, algae, and deep water. Figure 5 shows the bathymetry of the entire Study Area (National Ocean Service, 1990). The evaluation site is approximately 2-6 feet below sea level.

5. Data corrections.

Corrections to the digital images were accomplished according the following subtasks:

(a) Offsetting was the first modification made to the digital images. It is the process of making corrections for the movement of the plane (e.g. turbulence) and the subsequent interference to the image.

(b) *Noise* is defined by Curran (1985:238) as "random or regular effects in data which degrade its quality." Noise reduction is the process of correcting for this electrical interference, which can interfere with the overall analysis of an image.

(c) Coregistration of the bands is necessary to account for the fact that the four filters on the camera are slightly misaligned. These corrected images were assembled into a mosaic--combining images to form a continuous pictorial representation of the study area (Fig. 3 includes six mosaiced images).

(d) Georeferencing the images, or entire mosaic, is done for the purpose of producing a map. This procedure applies latitude and longitude lines, in addition to shifting the

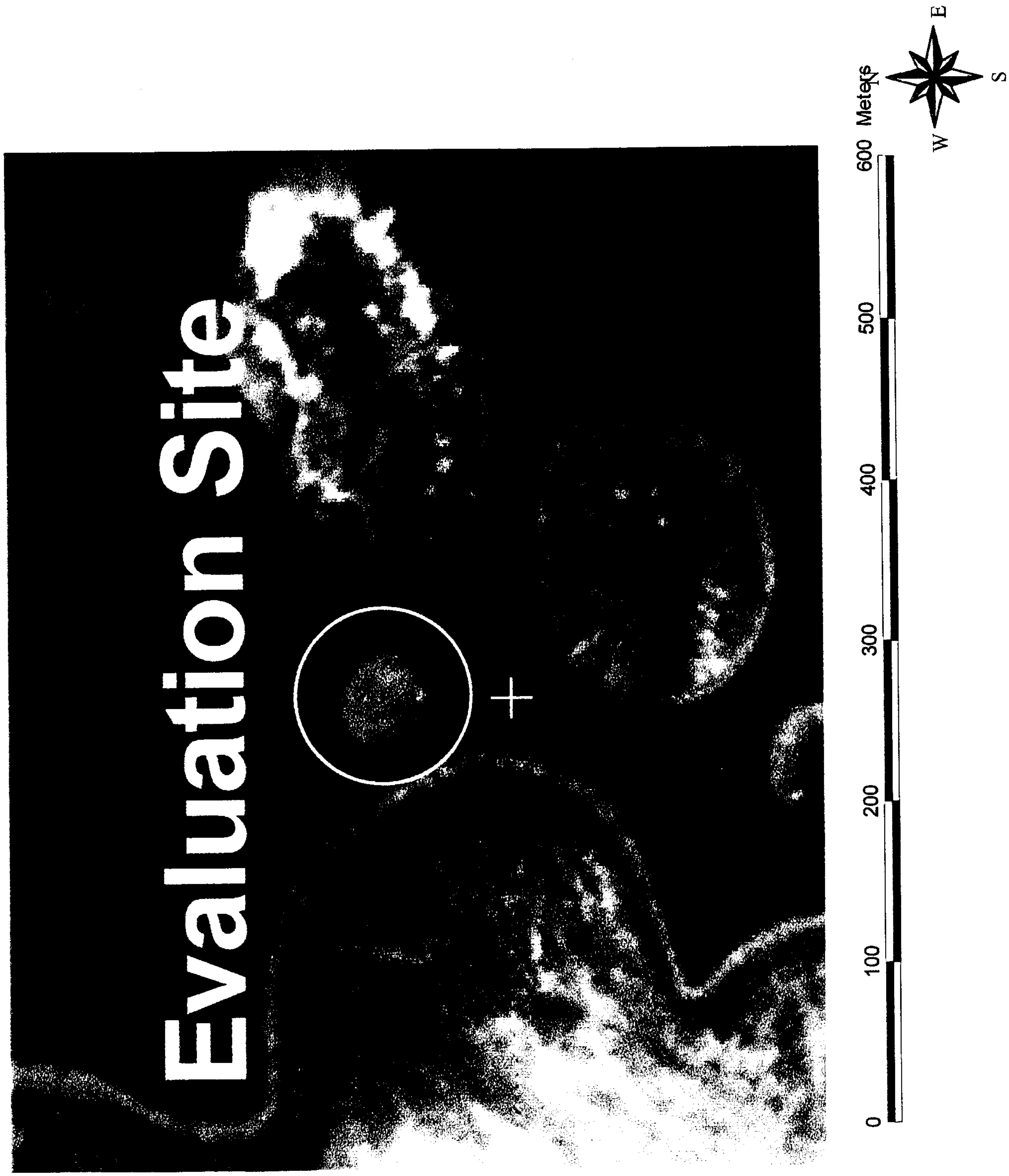


Fig. 4 Evaluation Site within Selected Study Area, Kaneohe Bay, O'ahu, Hawaii.

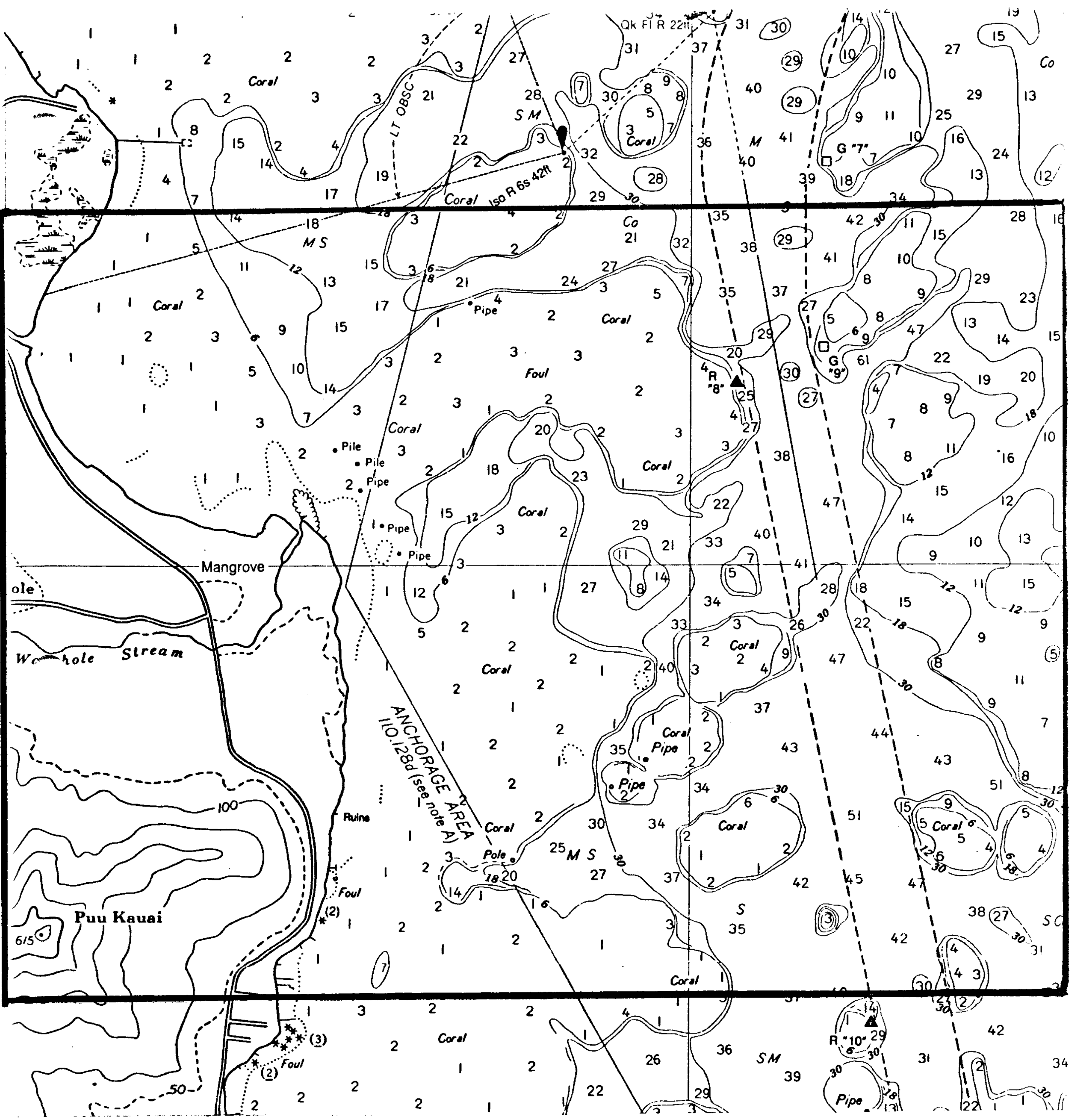


Fig. 5 Bathymetry of Study Area and surrounding waters within Kane`ohe Bay. Source: National Ocean Service, 1990. Scale 1 : 15,000 at Lat. 21°28′30″.

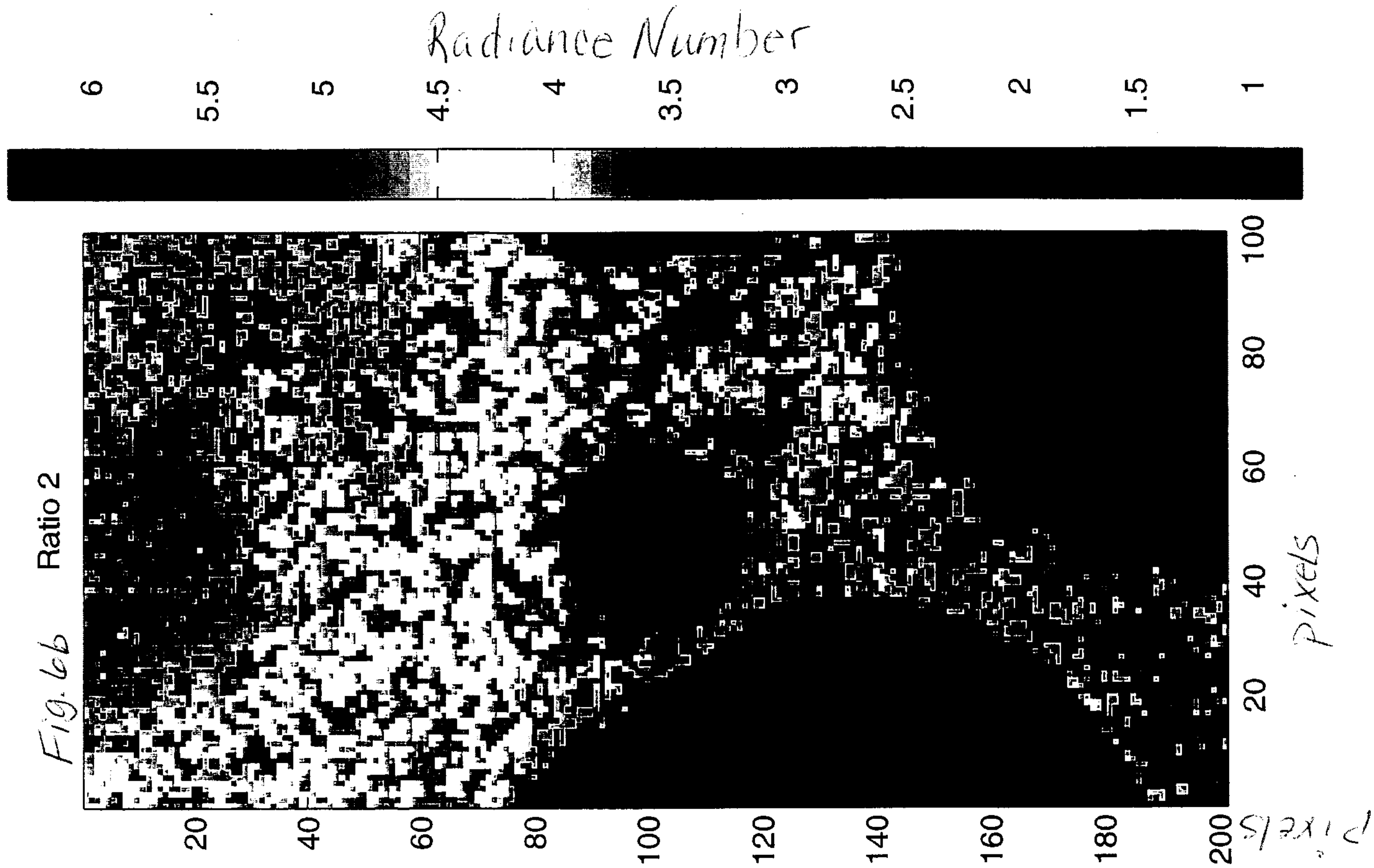
image according to the cardinal directions. This map is then employable by anyone in the world to locate its position on the globe. The map of my study area (Fig. 3) shows the positions of land, Waiahole Stream mouth, fringing reef, patch reefs (including the evaluation site), and the barrier reef within Kane`ohe Bay.

6. Data Analysis.

After necessary corrections are made to the images, they can be analyzed for various purposes with the use of remote sensing technology. The chosen patch reef, evaluation site (Fig. 4), was analyzed by Eric Hochberg, which included the identification of live coral, sand, and algae within the image. Hochberg is developing a computer algorithm that seems to determine these components very well. Although his work is unpublished, it involves a computer program that evaluates each pixel of an image. According to the band ratios he determined with each components' reflected wavelength, the computer program labels every pixel as live coral, sand, algae, or deep water. An average image consists of 1,710,880 pixels, therefore, the program, when fully completed, can analyze an image with great speed and precision.

III. RESULTS

Analysis and printouts of preliminary results of the evaluation site were conducted by Eric Hochberg. These analyses were attained by setting thresholds to maximize the differences in wavelengths for each material in order to classify them. Figures 6a and 6b display two different ratios, and are examples of how one multispectral image can be analyzed for different and distinct purposes. *Ratio 1* represents live coral



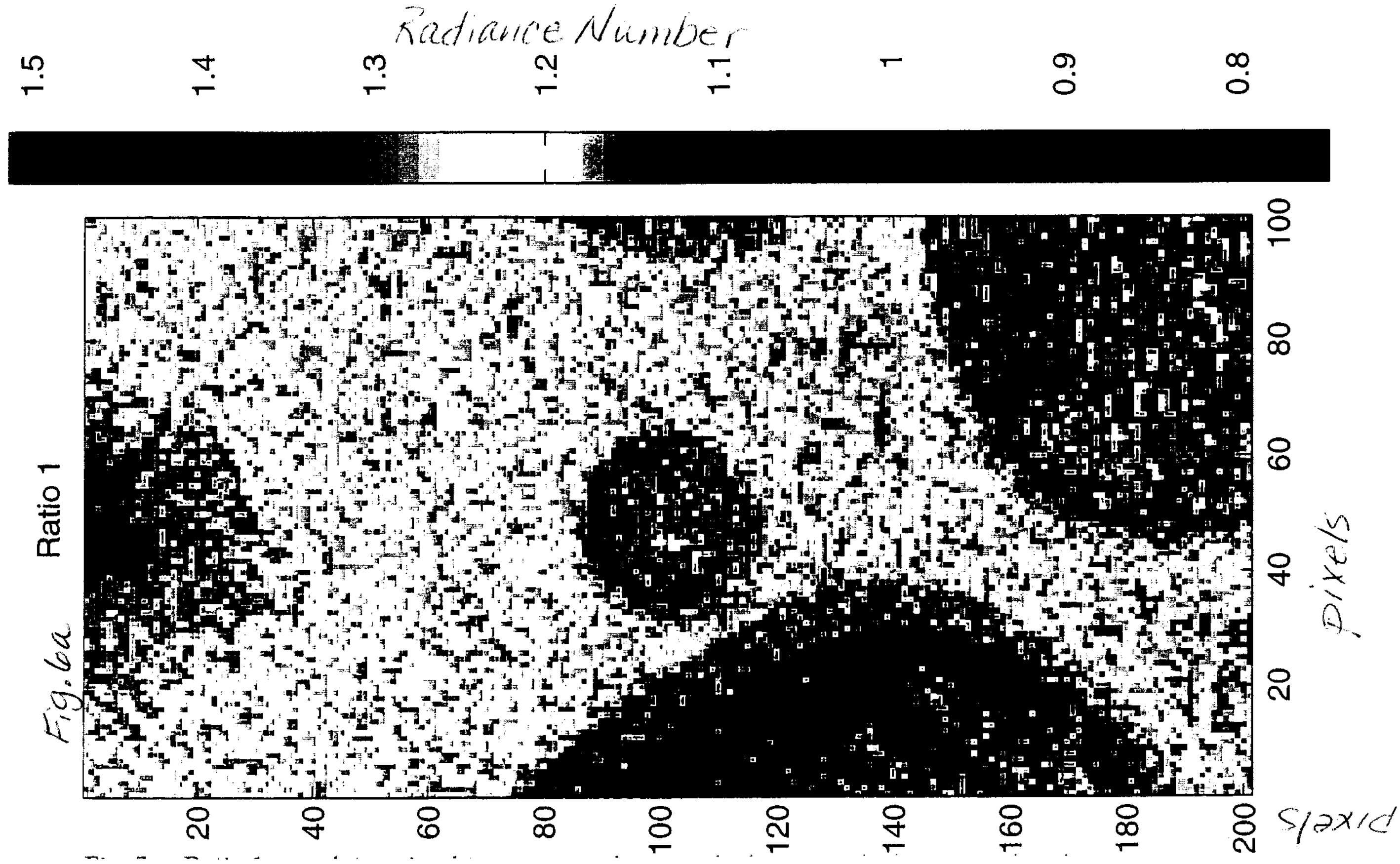


Fig. 6a Ratio 1 was determined to represent live coral, shown in dark blue with a data number <1.
Fig. 6b Ratio 2 represents chlorophyll (algae), shown in blue with a data number <2.5.

on the patch reef of the evaluation site. Coral is presented at the lower end of the spectrum in blue, algae in the middle of the spectrum as lighter blues and green, and deep water as yellow to red. *Ratio 2* represents the chlorophyll in the exact same image, which is an indicator of algae. The algae is shown as the dark blue in the lower end of the spectrum.

Figure 7 displays four components of the evaluation site. Brown represents living coral; green is algae; yellow is sand; and blue is deep water. Because it is analyzed pixel by pixel and assigned a label of coral, algae, sand, or water, a percent cover for each component may be attained. The measure of coral health, however, is subjective and dependent upon many factors. Therefore, an actual diagnosis of coral health will not be made at this time. However, this image documents the present condition of the patch reef and can be used to monitor changes in percent covers of each component over time. It is arguable that if the percent coverage of live coral decreases in the future, the health of that patch reef, and others adjacent to it, are declining in health and vigor.

Figures 6 and 7 are very preliminary results and accuracy is questionable. The interpreted or chosen classes derived from the remote sensing analysis can be tested for accuracy by comparing it with groundtruthing results.

IV. DISCUSSION

The results of the evaluation site show a low percent coverage of live coral and a high percent coverage of algae on the patch reef. This may be due to its proximity to the Waiahole Stream mouth and the input of pollutants from the stream flow. If more

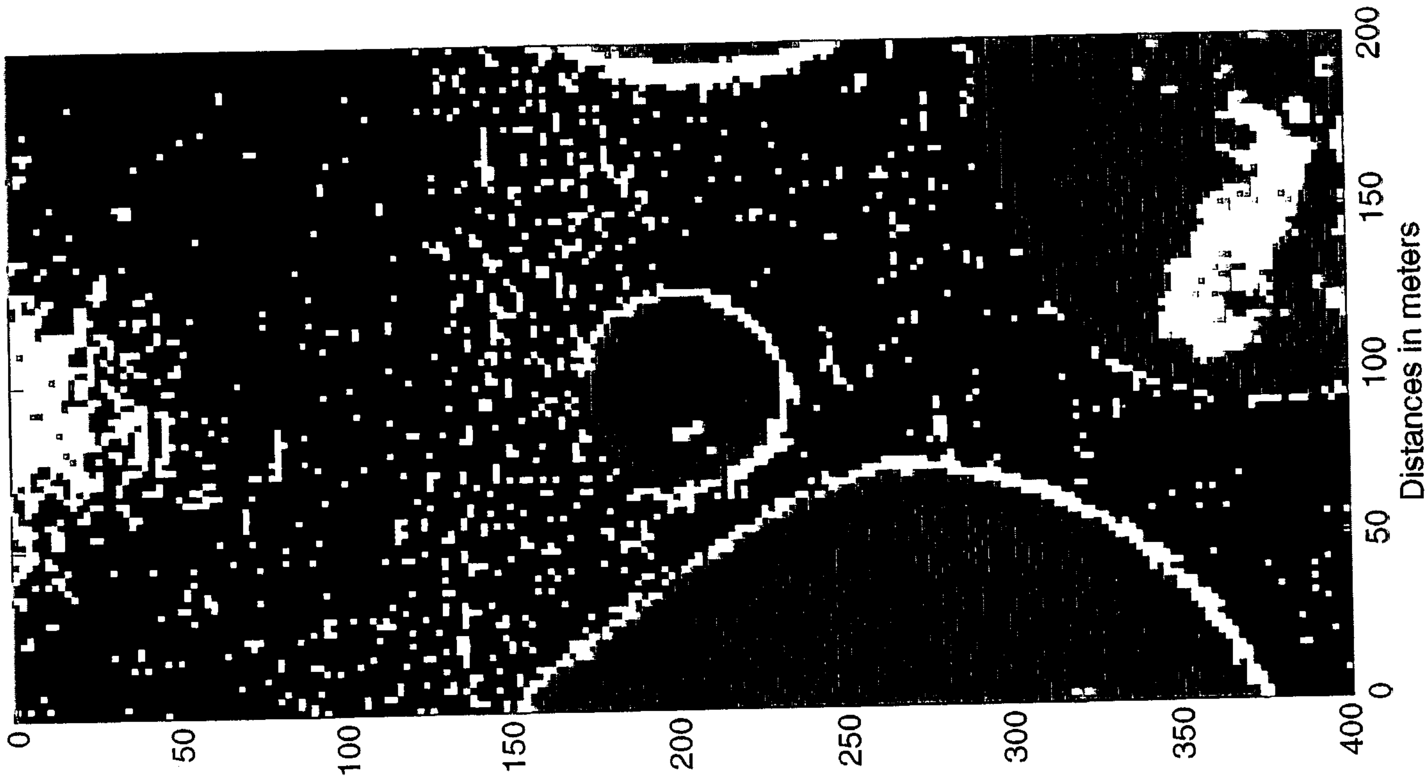


Fig. 7 Four components of evaluation site: brown = live coral; green = algae; yellow = sand; and blue = deep water.

anthropogenic developments occur on this surrounding land, there will be an increase of pollution carried into the bay via Waiahole Stream.

Although the health of the coral was not presently assessed, the documentation of the study area by remote sensing can be used for future comparison studies and the health of the coral may then be determined.

Remote Sensing Applications For Marine Environments

Large scale surveys of coral reefs are inherently difficult by conventional methods. Digital remote sensing has become of great interest to marine researchers, mappers, and monitors of coral reef environments. Most digital remote sensing research has been conducted with data provided by satellite multispectral scanners or with digitized aerial photographs. Remote sensing instruments obtain data in many different wavelengths of light, some that are beyond our visual range. Data of this type can be displayed on a computer in several different ways to map vegetation types, show location of mineral resources, and identify pollution sources, to name a few. The preciseness of remotely sensed data renders a sharply defined image that permits classification of coral, and other materials, abundance, and distribution.

KANE`OHE BAY

In order to fully understand why monitoring environmental changes in Kane`ohe Bay is important, a background of the area and the anthropogenic impacts need to be known. Kane`ohe Bay is the largest sheltered body of water in Hawai`i formed by a semi-enclosed embayment containing components of estuaries and coral reefs (Jokiel *et al.*, 1986). It lies on the northeastern side of the island of O`ahu, Hawai`i, located at

21°28'N; 157°48'W (Smith *et al.*, 1973). The Bay is approximately 12.8 km long, and 4.3 km wide (Smith *et al.*, 1973). It is surrounded by a narrow watershed demarked along the western side by the Ko`olau Mountain Range rising 500-850 m above sea level (Banner, 1974). The adjacent land basin, encompassing 46.6 km^2, is drained by 11 streams (Banner, 1974). The submarine topography and small tidal exchange cause poor circulation patterns, which Banner (1974), explains has heightened the effects of man upon the marine environment.

"The use and abuse of the land surrounding Kane`ohe Bay has obviously had a detrimental effect on the Bay" (Devaney *et al.*, 1976:210). The Kane`ohe Bay Master Plan Task Force (1992) substantiates that the effects of urbanization are dramatic. From 1940 to 1988, Kane`ohe area changed from a rural community to a residential community, increasing the population from 5,387 in 1940 to 54,903 in 1988 (Kane`ohe Bay Master Plan Task Force, 1992). This change in land use required more houses, streets, and sewers, displacing vegetated areas with more paved areas (K.B.M.P.T.F., 1992).

Smith *et al.* (1973) describe the first detailed observations of Kane`ohe Bay's biotic environment made in the late 1800's and 1900's. In 1880, the reef corals were noted as flourishing on the outer slopes of the fringing reef along the entire shoreline of the Bay. In 1918 and in 1928, it was said that the reef corals within the protected waters of the Bay were one of the best exhibitions of living corals to be seen. Thus, it appears that the impact of man upon the Bay was not severe until after the 1920's (Smith *et al.*, 1973:10).

The first major impact of modern western culture upon the bay's ecosystem occurred when large amounts of coral reef were dredged to create navigation channels and seaplane runways in preparation for World War II. Based on available records, it appears that a total of 15,193,601 cubic yards of material, mostly from coral reefs, was dredged from Kane`ohe Bay (Devaney *et al.*, 1976:116). "What has been destroyed in Kane`ohe Bay, because of the massiveness of that destruction, may possibly never be regained. What took nature eons to create has taken modern man only a few score years to lay waste" (Devaney *et al.*, as cited in K.B.M.P.T.F., 1992:6).

After the war, the watershed area about the bay has been continuously subjected to urbanization and modification. Agricultural development has also had a big impact by diverting streams for irrigation. This channelization of natural courses has exacerbated the fresh water discharge and sediment load problem of Kane`ohe Bay (Jokiel *et al.*, 1986; Banner, 1974). Of all the anthropogenic impacts, sewage discharge has had the greatest effect on Kane`ohe Bay's ecology. During W.W.II, with the development of the Kane`ohe Marine Corps Air Station (now Marine Corps Base Hawaii), sewage began being discharged into the bay with only primary treatment (Banner, 1974). Over 22,000$m^3$ gallons/$day^{-1}$ of sewage was estimated to have been entering Kane`ohe Bay until 1978 (Jokiel *et al.*, 1986:4). The effluent was diverted at that time; however, today small amounts of secondarily treated sewage continue to enter the north end of the bay.

The direct impact of the population boom to Kane`ohe Bay's aquatic environment has been increased erosion and runoff into the estuary, and marked eutrophication by massive sewage discharges (Banner, 1974). By 1974, Banner reported that one-third of

Kane`ohe Bay's coral had ceased growing, one-third was covered over by algae growths, leaving only one-third of the coral reefs relatively unaltered by the effects of urbanization.

Reefs are classified according to their location and proximity to land (Smith *et al.*, 1973) (Fig. 8). Along all of the shores are fringing reefs, interrupted only by stream mouths. Beyond the fringing reefs is a rather shallow lagoon, 10-15 m deep. Within the lagoon rise numerous patch reefs varying greatly in size. These areas are protected by an outerlying barrier reef, however, coral reef organisms are, in general, very vulnerable to environmental changes (Hochberg, in prep.).

Coral reefs are a magnificent and complex community of marine organisms. Through the formation of calcium carbonate skeletons, they are able to construct, modify, or maintain an entire shoreline environment (Smith *et al.*, 1973). Plants dominate the reef community and are therefore strongly dependent upon light (Smith *et al.*, 1973). For a reef ecosystem to survive for any great length of time, the constructive forces (healthy growth) must outdo the destructive forces (reef erosion) (Smith *et al.*, 1973).

The reef system in Kane`ohe Bay has many important functions: it supplies oxygen to the bay's water; provides fish habitats and food sources; and contributes to the biodiversity in the bay. The reefs also provide natural protection for human settlement areas and ports from natural coastal hazards. The primary use of the bay is recreational (Smith *et al.*, 1973). Sailing and water skiing are very popular and have become great tourist attractions. Moku o Loe (Coconut Island) in the southern section of the bay is the

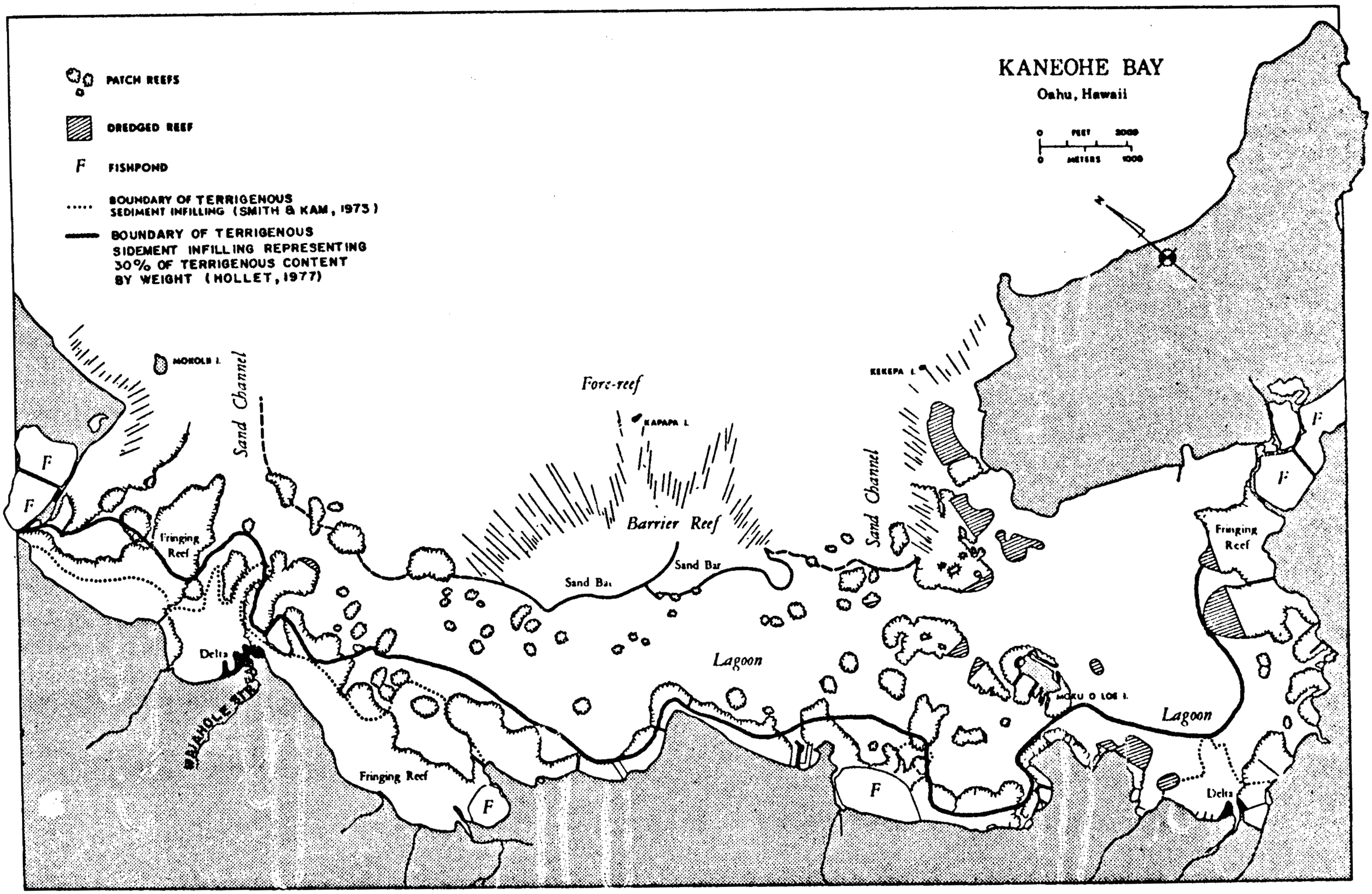


Fig. 8

Physiography of Kane'ohe Bay indicating reef system: fringing reefs, patch reefs, and barrier reef. Also indicated: the extent of terrigenous sediment infilling. M & E Pacific, 1985.

site of the laboratory of the Hawaii Institute of Marine Biology, a research unit of the University of Hawaii (Smith *et al.*, 1973).

◆ **Waiahole Stream Region**

Waiahole Stream is one of nine major streams that flow into Kane`ohe Bay (Fig.8) (M&E Pacific, 1985). Stream flow consists of direct runoff, as well as, groundwater flow from the Ko`olau dike complex (M&E Pacific, 1985) and averages 9 million gallons per day (K.B.M.P.T.F., 1992:12). The Waiahole Ditch-tunnel system, completed in 1916, was constructed at the head of the valley and transports water through the Ko`olau Range to the Ewa Basin (Devaney *et al.*, 1976). This diversion of Waiahole Stream has significantly reduced the base stream flow entering Kane`ohe Bay from the valley, over a long period of time. From 1956-58, it was recorded that the average daily discharge of Waiahole Stream had been reduce by about 60% since the figure recorded in 1912, prior to the ditch-tunnel construction (Devaney *et al.*, 1976:80). The ramifications of this anthropogenic interference have been the subject of much research regarding aquatic ecosystems and water quality. However, not much work can be found associated with the impact of the stream's reduced outfall to the bay environment and its coral reef.

Non-point source pollution via streams continues to impose stress upon Kane`ohe Bay's ecosystems. There is a long history of agricultural use of Waiahole Valley (M&E Pacific, 1985). Waiahole Stream transports sediments, fertilizers, and pesticides from the valley to the bay. Figure 9 shows how sedimentation can directly impact corals through smothering and the reduction of light transmittance as a result of increased turbidity. It

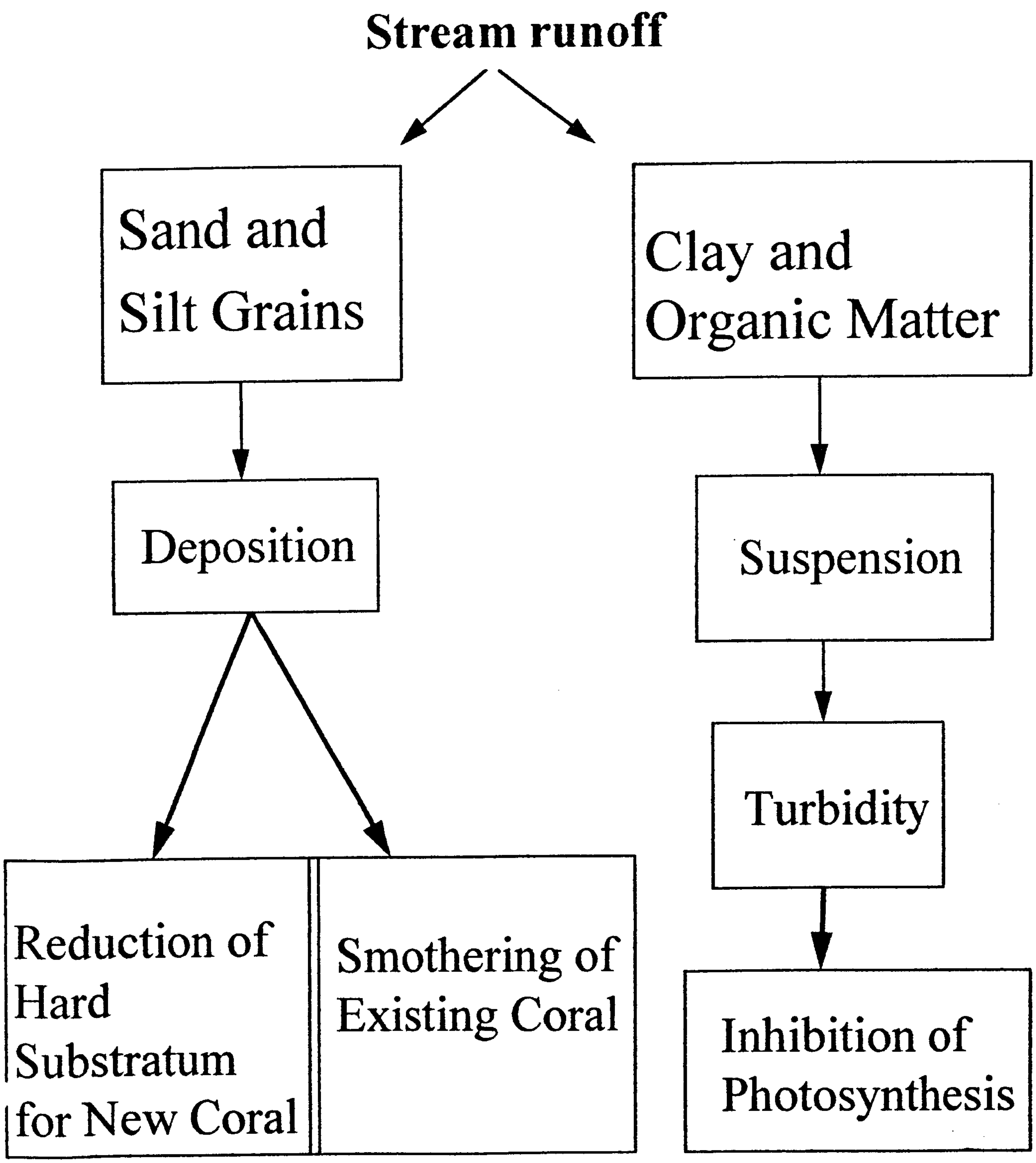


Fig. 9 Impact of sedimentation on coral.

can also indirectly impact corals through the reduction of exposed hard substrate for which young coral needs to grow (M&E Pacific, 1985).

Soil erosion is one of the major causes of sedimentation in Kane`ohe Bay. Prior to urbanization, most of the rain and flood water permeated the porous lava rock and slowly leaked into the bay (Smith *et al.*, 1973). Due to human modifications of the land's natural system, flood water is now confined to concrete conduits and enters the bay directly. "During rainstorms, sediment discharge into the bay can be tremendous" (Smith *et al.*, 1973: 11).

Other sources of sedimentation are calcium carbonate material from sand transport and reef erosion. The rapid erosion of the reefs is linked to urbanization of the watershed (Smith *et al.*, 1973: 11). A recent report produced by Smith and McMurtry (in press), shows the rate of sedimentation in 1994 in Kane`ohe Bay lagoon to be on average 1 cm/year. At least half of the sediment accumulation is of marine origin, as opposed to terrestrial. Evidence of substantial increases in the sedimentation rate in Kane`ohe Bay lagoon occurs between the late 1970's and mid 1980's (Smith and McMurtry, in press). According to Smith and McMurtry, the increase of sediments is most likely related to (a) human population growth (Fig. 10), (b) enhanced erosion in the Kane`ohe Bay watershed; and (c) enhanced calcium carbonate production and reduced calcium carbonate dissolution in the bay following diversion of the Kane`ohe sewage outfall in 1977.

The contribution of Waiahole Stream's sediment input to the bay has been estimated to be an average of 4,900 tons/year, constituting about 15% of the total

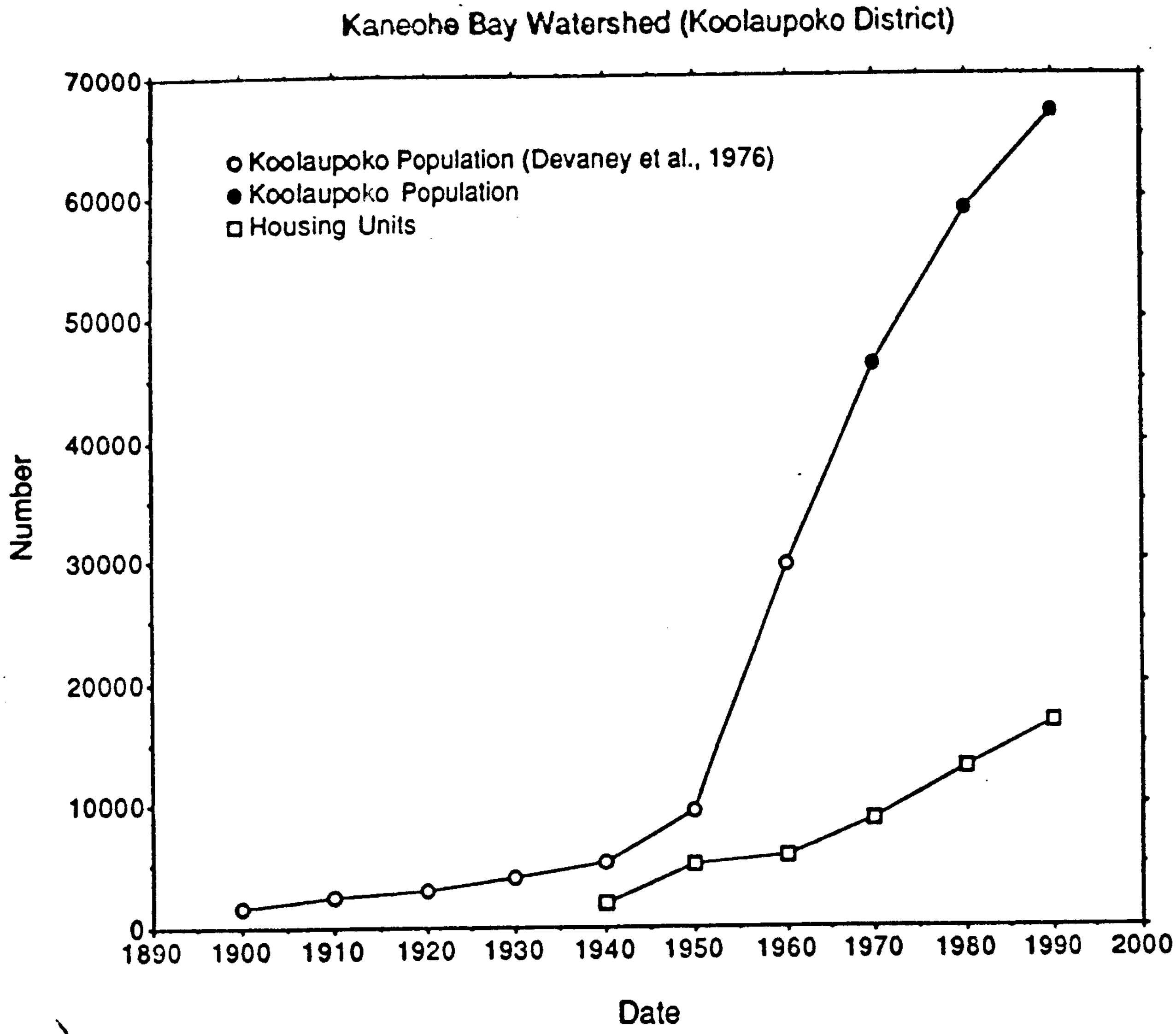


Fig. 10 Human population and the number of housing units in the Ko`olaupoko District (which is approximately equivalent to the Kane`ohe Bay watershed) from 1900 to 1990 (M & E Pacific, 1985).

sediment yield into Kane`ohe Bay (M&E Pacific, 1985). Most damage done to coral reefs in Kane`ohe Bay has resulted from periodic storm events and floods. Long-term sediment movement into the bay occurs because of an elevated proficiency of the storm flow to flush the stream bed of its silt and soil (M&E Pacific, 1985).

Agricultural runoff is a continuous source of nutrients to Kane`ohe Bay. The major constituents of fertilizer used in Waiahole Valley are nitrogen, phosphorous, and potassium (M&E Pacific, 1985). Excessive nutrients entering the bay environment cause eutrophication which adversely affects the health of marine ecosystems. There have been proposed agricultural expansions in Waiahole Valley, and if approved, will increase the input of nutrients transported by Waiahole Stream to the bay.

V. CONCLUSIONS

The entire Kane`ohe Bay environment has been subjected to numerous anthropogenic activities which have adversely affected its ecosystems. Kane`ohe Bay is important to Hawai`i because it is the largest estuary in the state and deserves special management and preservation. The area of Waiahole within the Kane`ohe Bay watershed has many valuable functions regarding the bay's environment, as well.

This research can be used as a baseline documentation of the Waiahole Stream mouth, and its present impacts on the coral reef in Kane`ohe Bay. Multispectral mapping of the coral in Kane`ohe Bay can be used as a way to monitor the health of its coral reef ecosystems and environmental recovery from urban impacts. This, in turn, can be used as a model for mapping other reef systems in the state, as well as globally. However, remote sensing is only one of a number of sources of information needed to perform well-grounded environmental management. It cannot provide all the information needed or wanted. It would be unreasonable to carry out resource investigations using remote sensing as the sole source of information (Kuchler *et al.*, 1988). A successful survey must integrate as many different types and sources of data as are relevant, useful and available (Kuchler *et al.*, 1988).

Sound marine resource planning and management needs up to date information, ideally no more than two years old (Kuchler *et al.*, 1988: 4). In our rapidly developing world today, monitoring the changes in our environment, especially human induced changes, is absolutely necessary to make proper management decisions. With the example of Waiahole Stream region of Kane`ohe Bay, this report exemplifies how remote sensing is a useful tool for monitoring environmental changes and aid in environmental management.

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